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Design of a Haptic Magnifier using an Ultrasonic Motor

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Abstract. The paper presents a serial architecture of an actuated manipulator which uses an ultrasonic motor. The serial architecture allows to modify the kinetic relationship between user's input and a tool. The design of the device is presented. A load, which exhibits fine details, is used in order to show how a zooming effect of its haptic rendering can be achieved with the haptic magnifier. Finally, the design is validated through an experimental analysis.

Keywords: Haptic, force-feedback, ultrasonic motor, piezoelectricity

1 Introduction

Human Controlled robots can be used to assist a Human user during manipulation tasks, when both the user and the robot hold a tool. By controlling the robot, some features can be programmed to facilitate the task from the user's point of view. For example, in [1], an actuated manipulator allows a packer to lift an object with low effort. In this application, the robotic arm reduces the amount of power required by the human user to move a heavy load, by magnifying the force he or she exerts, a technology named *extender* [2]. In [3], the authors report on a steady hand robot where the surgeon and the robot both hold the tool in a retinal microsurgery application. The robot filters out surgeon's tremor to achieve a better operation and reduce the rate of surgical complications. In [4], a robot assists in an arc welding task. The worker moves the welding torch, while the robotic assistant controls the displacement speed and the welding angles. In this particular applications, the assistance does not necessarily produce power. Instead, it modifies and improves user's trajectory.

Power assist or motion control robots often work in parallel with the user: the robotic assistance and the user's hand both have the same speed and position, and they share the required force[5]. To *extend* the capability of a user to manipulate a pay-load, user's force is magnified by the robot. The kinetic relationship between the user's hand and the tool is fixed, but the force-feedback is modified due to the assistance.

The goal of the haptic magnifier detailed in this paper is to facilitate more accurate task performance in small scale movements. In these applications, the user can exert the required amount of force, but he or she may have a limited dexterity to move the tool with precision. Hence, it is a problem of displacement, rather than a problem of force. This is why, the device changes the kinetic relationship: the displacement of the tool is a function of the displacement of the user's hand. However, due to its construction, the force produced by the user is equal to the force on the tool. Hence, the next section of the paper presents the working principle of the haptic magnifier. Then the design of our prototype is presented, to finally conclude with some experimental results.

2 Principle of the haptic magnifier

The haptic magnifier consists in using a serial architecture, where a motor is inserted between the tool and user's hand. By this way, the tool's speed v_o can be changed relatively to user's speed v_i , by controlling motor's speed. If inertial effect can be neglected, then this architecture ensures that at any time, the force applied by the tool f_o is equal to the force provided by the user's hand f_i . The figure 1 describes the serial architecture of the haptic magnifier. The figure 1)a shows the case of a tool directly manipulated by a user, and the case 1)b is the case of the serial architecture. In this example, v_o can be lower or higher than v_i but we have $f_o = f_i$.

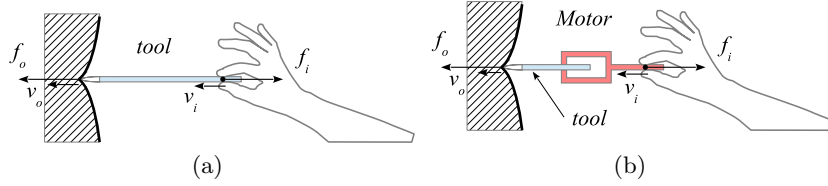


Fig. 1. A tool manipulated by a user (a) and a serial architecture with a motor inserted to achieve a haptic magnifier(b).

The haptic rendering of the mechanical load is the relationship between force and displacement, *i.e.* the relationship $f_o = F(x_o)$. If no haptic magnifier is used, then the haptic rendering can be summarized by equation 1:

$$f_i = f_o = F(v_o) = F(v_i) \quad (1)$$

When using the haptic magnifier, the relative speed between the load and the user's hand is controlled by the motor. If we name $k_M = \frac{v_o}{v_i}$ the speed ratio, the force perceived by the user is now given by:

$$f_i = f_o = F(v_o) = F(k_M \times v_i) \quad (2)$$

The figure 2 shows an example of a haptic rendering. The force f_o depends on the position x_o , with $\dot{x}_o = v_o$. In the same way, we define x_i the user's displacement. With the haptic rendering, we programmed a ratio $k_M < 1$, which means that the displacement x_o is lower than x_i . The force f_i can be deduced from the equation 2.

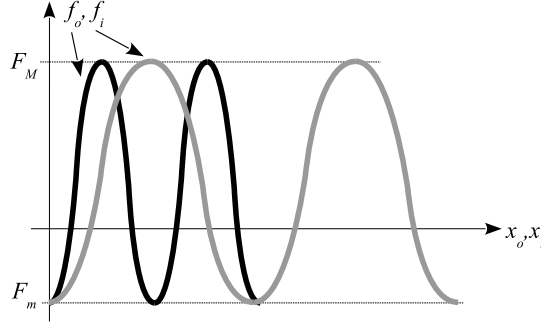


Fig. 2. An example of the resulting force versus displacement for $k_M < 1$; F_m and F_M are the maximum and minimum force of the load.

The power p_i which is produced by the human user can be compared to the power at the load p_o :

$$p_i = f_i \times v_i = f_o \times \frac{v_o}{k_M} = \frac{p_o}{k_M} \quad (3)$$

Hence, the power on the load can be:

- higher than the power at the user's hand if $k_M > 1$, meaning that user's hand moves slowly compared to the load,
- lower than the power at user's hand if $k_M < 1$, meaning that user's hand moves faster than the load.

Hence, the haptic magnifier is not a lever. Indeed, when levering a load, the equation 2 is modified, because the ratio k_M is applied on the velocity and on the force, and we have $f_i = k_M f_o$. The equation 2 then becomes:

$$f_i = k_M f_o = k_M F(k_M \times v_i) \quad (4)$$

The haptic magnifier changes the perception of a mechanical load attached to a tool, by changing the perceived spatial period. However, it doesn't change the level of the reaction force of the load, in opposition to a lever, which decreases the amount of force when achieving a zoom in of the explored load. We expect from a haptic magnifier that it helps to manipulate a load which contains fine details more easily, by using the magnifying effect.

3 Design of the haptic magnifier

The existing power assist robots, or force feedback devices, are fixed on a base. They work in parallel with the user, and thus, they don't have two terminals required for the tool and for the user. This is why, a specific device has been constructed. The main component of the haptic magnifier is the motor, which modifies the kinematic relationship between the user's input velocity v_i and the velocity of the tool v_o . The speed of the motor is equal to $v_M = v_i - v_o = (1 - k_M)v_i$. The power produced by the motor is given by $p_M = f_i \times v_M$; the power p_M can then be positive or negative, depending on the force f_i and the speed differential v_M . Hence, it actually is a motor which is needed to actuate the tool ($p_M > 0$) or to brake it ($p_M < 0$).

Among the possibilities to actuate the haptic magnifier, Ultrasonic Motors [7] are good candidates since they are more a source of speed than a source of force. Ultrasonic motors use high frequency (above 20kHz) and low amplitude vibrations to push a slider by friction. By controlling the amplitude of vibration, we can control the speed of the motor. The device chosen in the experimental realization is a linear PI-Motor M-661 from Physic Instrumente, which is able to drive a load at 2N and 0.5m/sec.

However, they are not ideal sources of speed. Indeed, if the force in opposite direction to the speed increases, the motor's speed is reduced, with an almost linear behaviour [8]. Closed loop control is thus inevitable. Hence, the experimental setup uses two linear position sensors: one measures x_i , the position of the input, and the other measures the position of the motor x_M ; x_o is obtained with $x_o = x_m + x_i$. The experimental setup is presented in figure 3.

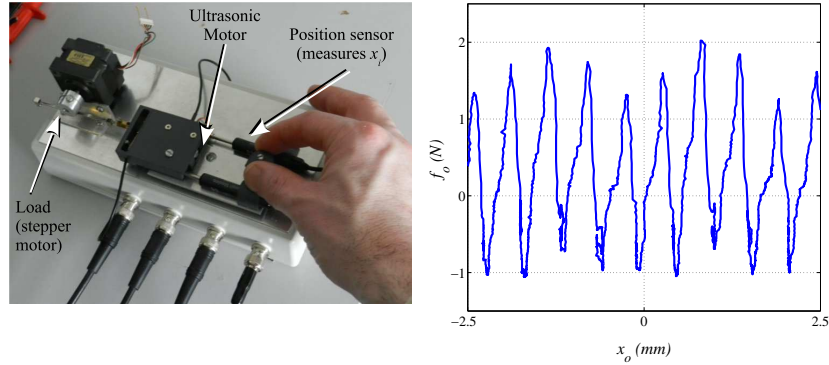


Fig. 3. Realization of the haptic magnifier; left: the experimental setup (the load cell is not visible); right: output force of the load as a function of the position.

To achieve the load, one end of a steel ruler is attached at the output of the haptic magnifier, and the other is attached to the rotor of a stepper motor. The

stepper motor is never energized; however, when moving the ruler, the rotor of the stepper motor rotates, producing a reaction torque (known as the cogging torque), even though it is not powered. A load cell can measure the force induced by the stepper motor, and the force exerted by the load is presented in figure 3. The force f_o can be positive (the user has to push on the tool to move the load) or negative (the user has to brake the tool to maintain a constant speed), leading to an instantaneous power p_o which can be positive or negative. Moreover, fine details are produced by the load. Indeed, 9 stable positions are counted over $5mm$; and equivalent grating with a spatial period of approximately $550\mu m$ would give rise to the same amount of stable position.

4 Experimental results

We tested the haptic magnifier with a zooming effect only ($k_M < 1$), and figure 4 compares the resulting haptic rendering f_i as a function of x_i and f_o as a function of x_o for $k_M = 0.2$. We still assume that $f_i = f_o$.

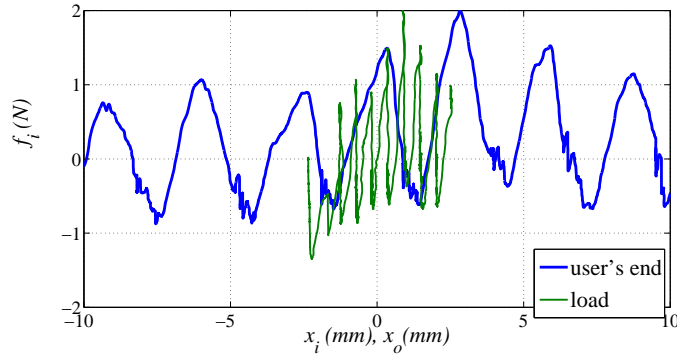


Fig. 4. Resulting rendering for $k_M = 0.2$; bold blue line is $f_i = F(x_i)$ at user's terminal, green line is $f_o = F(x_o)$ at the load.

The figure shows how the stable positions of the load are now placed at longer distance from each other on user's point of view. This highlights the property of the haptic magnifier to modify the haptic rendering of the load, without changing the level of its reaction force.

We then asked several users (4 males, 1 females, aged 24 to 31) to try the haptic magnifier. The participants were grasping the user's handle with two fingers (between the forefinger and the thumb). In some conditions (conditions 1 and 2), the hand could rest on the table where the tool and the load are lying. In other conditions (condition 3 and 4), the participants were not allowed to rest their hand on the table. In these conditions, moving the user's handle is less comfortable, because user's position is constrained. In conditions 1 and 3,

the haptic magnifier is switched off, leading to $k_M = 1$, and the participants are touching the load through the tool. In conditions 2 and 4, the haptic magnifier is switched on, with $k_M = 0.2$

During the experiments, the participants followed a training session of about 3 minutes to recognize the load and feel the stable positions, which are named "steps". They are then asked to move the tool 4 steps along forth and backward directions as fast as possible during 80 seconds. We recorded the movement of each participant for the last minute, and we post-processed the number of successful displacements (those with 4 steps only), and the number of overshoots (the displacements which count more than 4 steps). The results are presented in figure 5.

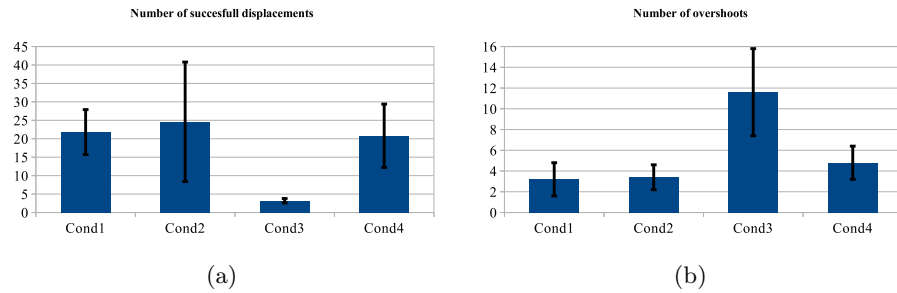


Fig. 5. Average numbers of successful displacements (a) and overshoots (b) for each experimental condition.

The results show that using the haptic magnifier did not improve the performances of the participants when the hand could rest on the table. Indeed, the average number of successful displacements and overshoots for Conditions 1 and 2 is almost the same. However, the control of the tool is made easier with the haptic magnifier. Indeed, without the haptic magnifier, we noticed that the tips of the fingers which are grasping the user's handle become white, showing that the participants applied larger forces in opposition. To obtain a better control, they are tenser on the user's handle. This effect disappears with the haptic magnifier.

When the hand cannot rest on the table, which constrains more the position of the participant's hand, the participants obtained a very low success rate without the haptic magnifier (condition 3), and they did a large number of overshoots. In fact, some participants could not achieve any successful displacement. In opposition, with the help of the haptic magnifier (condition 4), the participant could obtain a number of successful displacements similar to the conditions 1 and 2, with slightly more overshoots.

At the end of the experiment, we asked the participants to designate the condition which allows them to complete the task more easily. Four participants (out of five) designated the condition 2 (hand on the table and the haptic magnifier).

5 Discussion and conclusions

In this paper, we present the haptic magnifier, which is a serial architecture of a human controlled robot with one degree of freedom. The control of the haptic magnifier allows to change the haptic rendering of a load, without modifying the level of force applied on it. The experimental study shows how the detectable steps of a load can be enlarged to the user's point of view.

The benefit of the haptic magnifier during the exercise depends on the position of the hand. It can improve the comfort of the user when the hand can rest. Or, it can even be necessary to control the tool when the hand does not rest.

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